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Transient Techniques for Battery Impedance Measurements

Small-Amplitude Exponential Perturbation Technique

Prepared by

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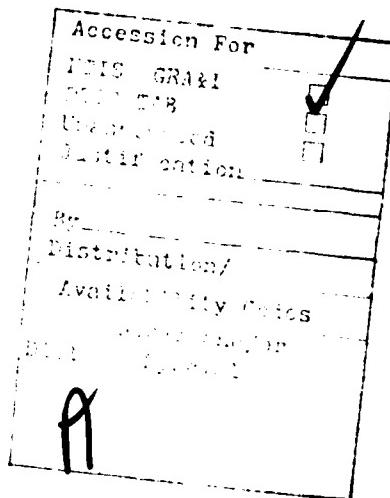
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) A perturbation technique is reported for measuring the impedance of battery cells under conditions of controlled potential. The small amplitude exponential perturbation (SAEP) technique is applicable over an extremely wide frequency range and appears to be the method of choice for measuring the impedance of battery cells that contain very little stored electrochemical energy.		

CONTENTS

I.	INTRODUCTION.....	5
II.	THEORY OF SAEP.....	7
III.	RESULTS.....	11
IV.	CONCLUSIONS.....	17
APPENDIX		
FORTRAN PROGRAM FOR SAEP IMPEDANCE CALCULATION.....		19



FIGURES

1. Voltage Perturbation and Response Current for Dummy Cell..... 12
2. Impedance of Dummy Cell from Data of Fig. 1..... 13
3. Voltage Perturbation and Current Response for Nickel Cadmium Cell at 0.5 V..... 15
4. Impedance of Nickel Cadmium Cell from Data of Fig. 3..... 16

I. INTRODUCTION

The proper operation of battery cells invariably depends on a number of internal physical and chemical reactions occurring at rates that are sufficient to sustain cell performance. These reactions typically involve charge transfer processes at the electrodes, as well as diffusional transport of materials to the active electrode surfaces. Kinetic measurements permit determination of the relative importance of these processes in controlling cell performance. The most general method for making these kinetic measurements is to measure the electrical impedance of the battery cell as a function of frequency. The rates of the various processes that affect the cell voltage are inferred directly from the frequency dispersion of the cell impedance.

A number of techniques have been used to measure the impedance of battery cells. The most commonly used is that of applying a sinusoidally varying ac signal to the battery cell and monitoring the cell response in terms of amplitude and ac phase shift. This ac method is relatively easy to use, but if data are required over a wide frequency range or at very low frequencies, it becomes somewhat cumbersome. Other techniques for impedance measurements of battery cells incorporate perturbing functions other than sinusoidal ac. For example, in the galvanostatic transient technique¹ a step change in the current passing through the cell is applied, and the response of the cell to the current change is measured. The relationship between the change in cell current and the voltage response gives the cell impedance. This technique is particularly useful when the cell contains appreciable stored capacity, since in this case controlling cell current is much easier than controlling cell voltage. However, when the cell contains very little stored capacity, any measurement attempted under conditions of constant current may change the cell voltage by a large amount and thereby appreciably alter the chemical state of the cell. In this situation, it is desirable to employ a potentiostatic

¹A. H. Zimmerman and M. R. Martinelli, Transient Techniques for Low Frequency Impedance Measurements, TR-0079(4970-10)-1, The Aerospace Corporation, El Segundo, Calif (6 October 1978).

technique that involves the application of a controlled perturbation to the cell potential.

We have developed and applied such a technique to battery cells. This technique is called small amplitude exponential perturbation (SAEP) and involves perturbing the cell voltage with a small amplitude (<5 mV) exponential signal while measuring the current response of the cell. Again, the cell impedance is obtained from the relationship between voltage and current. This technique can be used to measure the impedance of battery cells at any voltage or state of charge that is accessible to them, although very large currents (and power supplies) may be involved when the cell has appreciable active electrochemical capacity.

II. THEORY OF SAEP

Any potentiostatic transient technique for measuring impedance employs a transient potential function $V(t)$. This potential function is applied as a perturbation to a battery cell that has the initial potential V_0 . The cell current is initially $I_0 + I_N(t)$, where I_0 is the steady-state current at V_0 , and $I_N(t)$ is any change in current resulting from depletion of the stored electrochemical capacity of the cell at the initial voltage. After the perturbation $V(t)$ is applied, the current is $I_0 + I_N(t) + I(t)$. For this analysis to be correct, the amplitude of $V(t)$ must be sufficiently small that $I_N(t)$ does not change appreciably in response to $V(t)$. This means that typically $V(t)$ should be less than 5 mV in amplitude. In addition, the time constant associated with $I_N(t)$ must be much greater than that associated with $I(t)$ so that they can be separated in time.

The impedance as a function of time is then directly given by Ohm's law

$$Z(t) = \frac{V(t)}{I(t)} \quad (1)$$

However, the cell impedance is more conveniently analyzed in the frequency domain. Laplace transformation of $V(t)$ and $I(t)$ permits us to obtain the impedance as a function of frequency.

$$Z(\omega) = \frac{V(\omega)}{I(\omega)} \quad (2)$$

where $V(\omega)$ and $I(\omega)$ are the Laplace transforms of voltage and current, respectively.

The digital Laplace transforms required are calculated from the voltage and current data,

$$F(\omega) = \int_0^\infty f(t) \exp(-j\omega t) dt = \sum_i \int_{t_i}^{t_{i+1}} f_i(t) \exp(-j\omega t) dt \quad (3)$$

which are digitized by computer into arrays having i data points, each corresponding to a given time. The function $f_i(t)$ fits the data for $f(t)$ in the interval t_i to t_{i+1} and may be any convenient function that fits the data. Functions used for $f(t)$ include linear, quadratic, and exponential forms as follows.

1. Linear: $f_i(t) = A_i t + B_i$

$$A_i = \frac{f(t_i) - B_i}{t_i}$$

$$B_i = \frac{[f(t_{i+1}) - t_{i+1}/t_i f(t_i)]}{1 - \frac{t_{i+1}}{t_i}} \quad (4)$$

2. Quadratic: $f_i(t) = L_i t^2 + M_i t + N_i$

$$M_i = [\frac{\Delta f_{12}}{\Delta t_{12}^2} (\frac{t_1^2}{t_{i+2}} - t_{i+2}) - \frac{\Delta f_{13}}{t_{i+2}}] [1 - (t_{i+2}) \frac{\Delta t_{12}}{\Delta t_{12}^2} + \frac{t_i}{t_{i+2}} (\frac{t_i \Delta t_{12}}{\Delta t_{12}^2} - 1)]^{-1}$$

$$L_i = \frac{\Delta f_{12}}{\Delta t_{12}^2} - M_i (\frac{\Delta t_{12}}{\Delta t_{12}^2}) \quad (5)$$

$$N_i = f(t_i) - L_i t_i^2 - M_i t_i$$

where

$$\Delta t_{12} = t_i - t_{i+1}$$

$$\Delta t_{12}^2 = t_i^2 - t_{i+1}^2$$

$$\Delta f_{12} = f(t_i) - f(t_{i+1})$$

$$\Delta f_{13} = f(t_i) - f(t_{i+2})$$

3. Exponential:

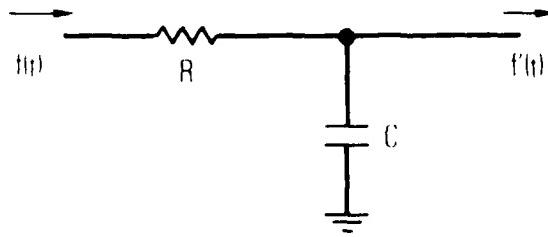
$$f_i(t) = C_i \exp(-a_i t) \quad (6)$$

$$a_i = \ln \left[\frac{f(t_{i+1})/f(t_i)}{t_i - t_{i+1}} \right]$$

$$C_i = f(t_i) \exp(a_i t_i)$$

The exponential function of Eq. (6) gave the best results for all data that were not near a point where $f(t)$ crossed zero. A listing of a Fortran program for doing the transformations that give the impedance is provided in the Appendix.

Actual experimental data contain noise; in particular, 60-Hz noise may pose a problem when small changes in voltage or current are being monitored. The simplest way to eliminate this kind of noise is with an RC filter.



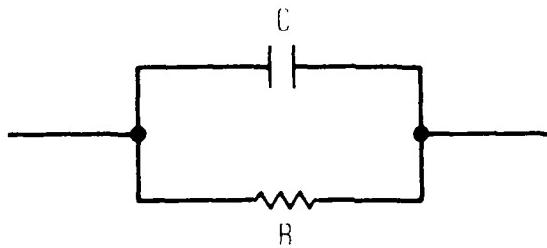
However, the transfer function of this filter must then be deconvoluted from the data. This is easily done in the frequency domain simply by multiplying the transformed function by the inverse filter function transform

$$f(\omega) = f'(\omega) (1 + j\omega\tau_F) \quad (7)$$

where $\tau_F = RC$ is the filter time constant.

III. RESULTS

The impedance of battery cells below 1 kHz is generally capacitive in nature, behaving as an equivalent parallel RC circuit where the values of R and C may have a complicated dependence on frequency. The results of an SAEP experiment on a simple dummy cell consisting of the RC circuit



where $C = 1 \text{ F}$ and $R = 10 \Omega$ are examined first. For simplicity, let us assume that $V_0 + V_N(t)$, the initial cell voltage, is zero. An increasing exponential perturbation having amplitude α and time constant τ is applied to the cell

$$V(t) = \alpha(1 - e^{-t/\tau}) \quad (8)$$

$V(t)$ and the current response of the dummy cell $I(t)$ are indicated in Fig. 1 for $\tau = 2\text{s}$, $R = 10 \Omega$, and $C = 1 \text{ F}$. $I(t)$ is given by the relationship

$$I(t) = \frac{\alpha}{R} \left[1 - \left(1 - \frac{RC}{\tau}\right) e^{-t/\tau} \right] \quad (9)$$

Note that the values of R and C do not influence the time constant for current decay, but only control the amplitude of the current transient. From the time-dependent voltage and current functions, the impedance is calculated, with the results shown in Fig. 2 in the complex plane. The results in Fig. 2 agree with the theoretical result for the impedance

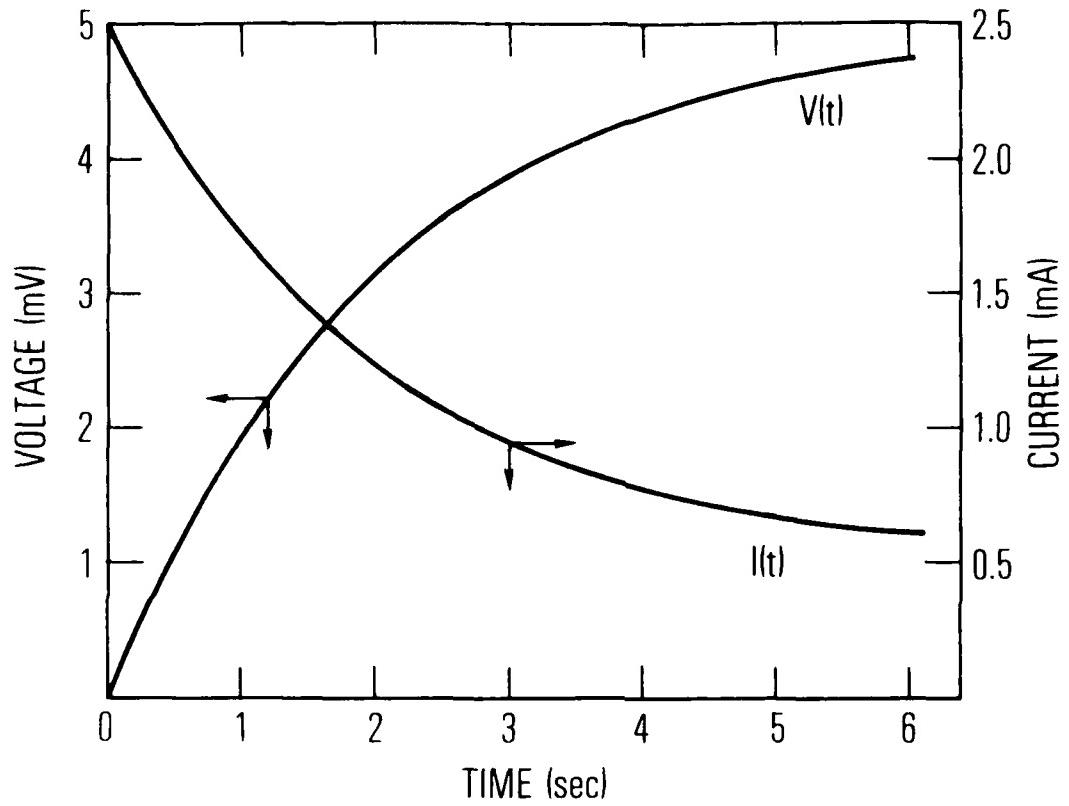


Fig. 1. Voltage Perturbation and Response Current for Dummy Cell

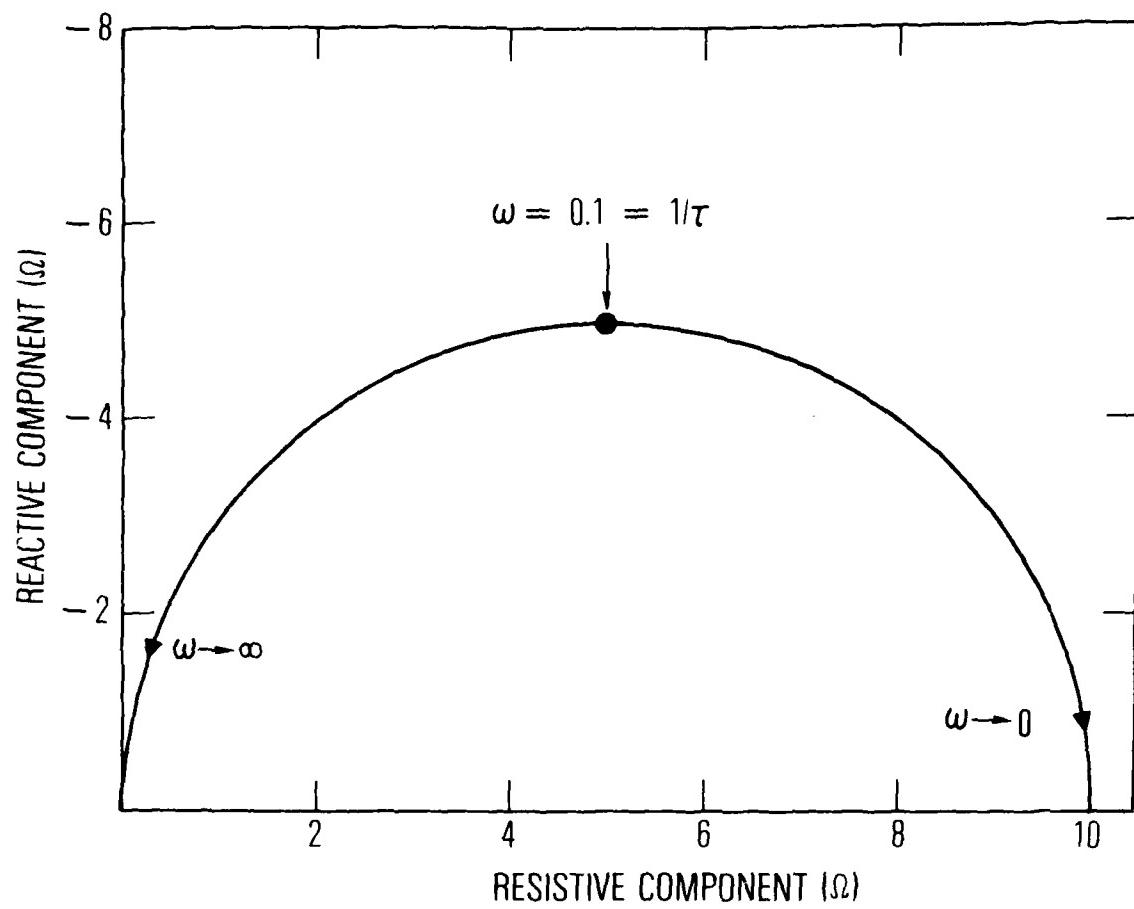


Fig. 2. Impedance of Dummy Cell from Data of Fig. 1

$$Z(\omega) = \frac{R}{1 + j\omega RC} \quad (10)$$

This simple example illustrates that the expected current response for a battery cell consists of a rapid rise to a maximum, followed by a decay to a steady-state current that is different from the initial current by the amount α/R . The magnitude of the peak current is controlled by the relative time constants of the exponential perturbation and the cell, and is given by $\alpha C/\tau$ in the preceding example. Thus, the experimental maximum transient current can be controlled simply by controlling the perturbation time constant.

The results obtained when an exponential perturbation is applied to a nickel cadmium cell are shown in Fig. 3. The nickel cadmium cell used was a 10-Ah prismatic cell, and the initial cell voltage was 0.5 V. The impedance is indicated in the complex plane in Fig. 4. In making these measurements, it was found that signal to noise became relatively poor unless the time constant of the applied perturbation was the same order of magnitude as the relaxation time for the battery cell. With this general requirement satisfied, the SAEP technique provides a convenient method for making impedance measurements on battery cells over an extremely wide range of frequencies, under conditions of battery operation for which potential control is acceptable.

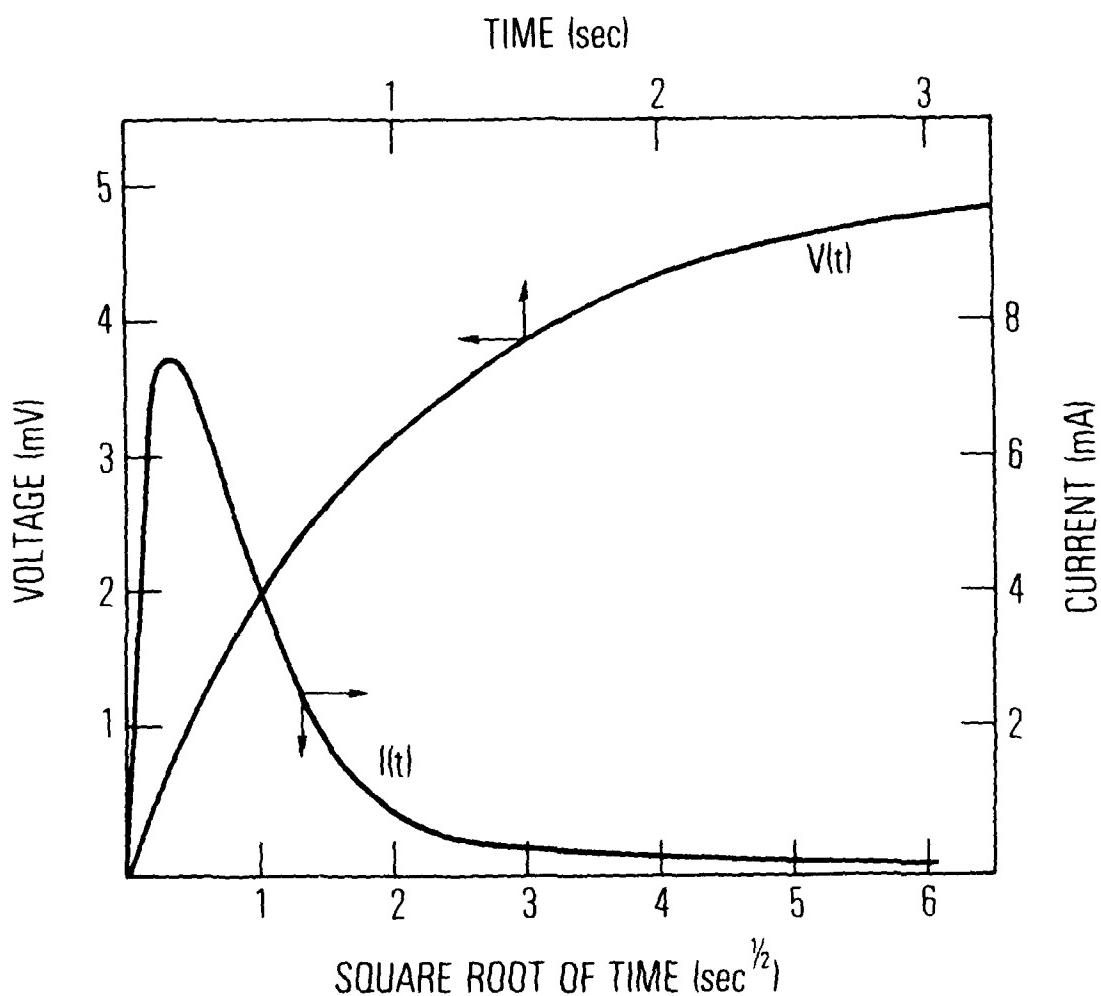


Fig. 3. Voltage Perturbation and Current Response for Nickel Cadmium Cell at 0.5 V

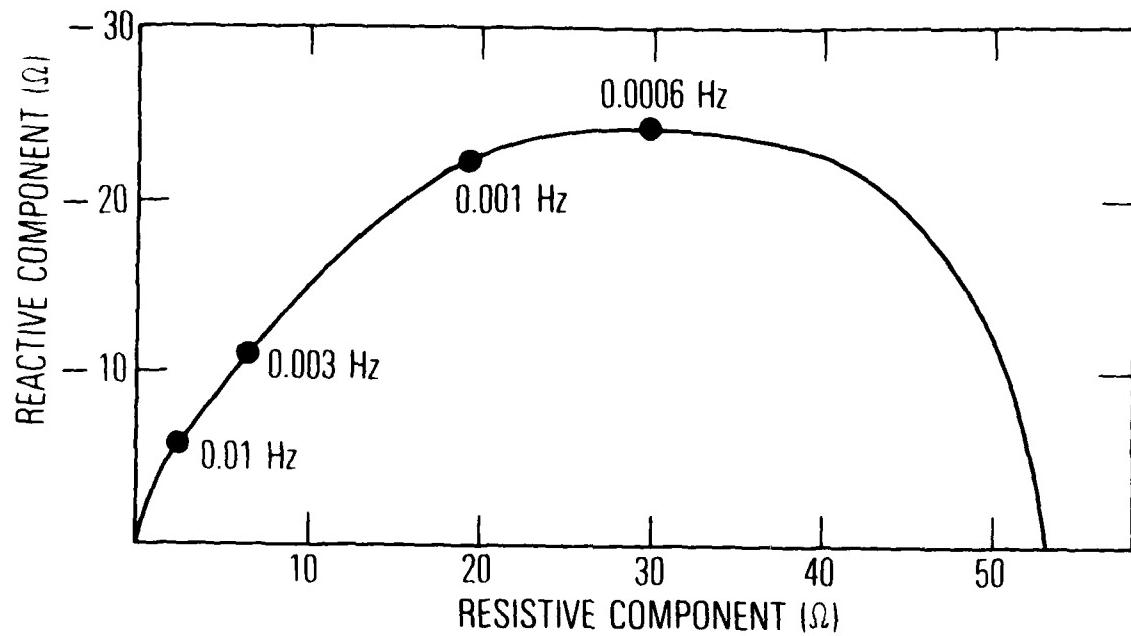


Fig. 4. Impedance of Nickel Cadmium Cell from Data of Fig. 3

IV. CONCLUSIONS

The SAEP technique has been developed and applied to measuring the impedance of battery cells under conditions of controlled potential. This appears to be the optimum method for measuring the impedance of battery cells that contain little stored electrochemical capacity.

APPENDIX

FORTRAN PROGRAM FOR SAEP IMPEDANCE CALCULATION

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PROGRAM SAFF (INPUT,OUTS,UT,TAPE5=INPUT,TAPE6=OUTPUT)
 THIS PROGRAM CALCULATES IMPEDANCE AS A FUNCTION OF FREQUENCY FROM
 AN EXPONENTIAL VOLTAGE PERTURBATION AND ITS CURRENT RESPONSE USING
 THE LAPLACE TRANSFORMATION TECHNIQUE.
 A FILTFF FUNCTION MAY BE INCLUDED IN THE CURRENT RESPONSE, AND IS
 DECONVOLUTED FROM THE TRANSFORM.

THE PROGRAM FITS THE DATA TO A MAXIMUM OF TWO DIFFUSION PROCESSES. IT REQUIRES INITIAL GUESSES FOR THE FITTING PARAMETERS S1 AND S2, WARBURZ COEFFICIENTS A1 AND A2, AND CAPACITANCES C1 AND C2 AS WELL AS ELECTROLYTE RESISTANCE RZ.

DATA INPUTS ARE IDENTIFIED BY NUMBER
 MPROB = EXPONENT IDENTIFICATION NUMBER
 NDATV = NUMBER OF VOLTAGE DATA POINTS
 NDATI = NUMBER OF CURRENT DATA POINTS
 TSADP = NOMINAL PERTURBATION TIME CONSTANT IN SECONDS
 AMPV = AMPLITUDE OF EXPONENTIAL PERTURBATION IN MV
 AMPI = AMPLITUDE OF CURRENT CHARGE AT INFINITE TIME IN MA
 FILTC = TIME CONSTANT OF FILTER USED FOR VOLTAGETIME DATA (SEC)
 FILTV = TIME CONSTANT OF FILTER USED FOR CURRENTTIME DATA (SEC) AND
 VV(I), X(I), TSV(I) ARE ORDERED PAIRS CORRESPONDING TO TIME (SEC) AND
 EXFON(FONTIAL) ZERO AT ZERO TIME AND APPROXIMATELY INFINITE
 X(I), TSV(I) ORDERED PAIRS CONSISTING OF THE SQUARE ROOT OF
 TIME AND CURRENT DATA (MA), AND SHOULD BE ZERO AT ZERO TIME
 AND XTC AT INFINITE TIME
 COMMON/A/A1,S1,C1,B1,S2,C2,VV(200),TSV(4000),F(200)RZ
 COMMON/2/NP,G0,P,PS(/)
 COMPLEX/ZM(200),VH,XIH,P,FFF,VFF
 EQUIVALENCE (ZM, WRC1, WRC2, WFINV,U1,U4,U10,1.E,40.0/
 DATA WRC1, WRC2, WFINV,U1,U4,U10,1.E,40.0/
 SWITCH=0 GIVES IMPEDEANCE CALCULATION ONLY
 SWITCH=1 GIVES IMPEDEANCE CALCULATION AND FIT TO MODEL

```

      300  READ(5,201) MPROB,NDATV,NDATI,TSADP,AMPV,AMPI,FILTC,FILTIV
      301  IF(MPROB.EQ.0) 1000,301
      302  CONTINUE
      303  WRITE(6,60001) MPPOR
      304  WRITE(6,70001) TSADP,FILTC
      305  WRITE(6,70002) AMPV,AMPI
      306  READ(5,2007)(TSV(I),VY(I),I=1,NDATV)
      307  READ(5,2008)(TSV(I),XI(I),I=1,NDATI)
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      766  WRITE(6,70461)
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      768  WRITE(6,70463)
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      779  WRITE(6,70474)
      780  WRITE(6,70475)
      781  WRITE(6,70476)
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      783  WRITE(6,70478)
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      790  WRITE(6,70485)
      791  WRITE(6,70486)
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      804  WRITE(6,70499)
      805  WRITE(6,70500)
      806  WRITE(6,70501)
      807  WRITE(6,70502)
      808  WRITE(6,70503)
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      811  WRITE(6,70506)
      812  WRITE(6,70507)
      813  WRITE(6,70508)
      814  WRITE(6,70509)
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      816  WRITE(6,70511)
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      818  WRITE(6,70513)
      819  WRITE(6,70514)
      820  WRITE(6,70515)
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      823  WRITE(6,70518)
      824  WRITE(6,70519)
      825  WRITE(6,70520)
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      827  WRITE(6,70522)
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      866  WRITE(6,70561)
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      868  WRITE(6,70563)
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      870  WRITE(6,70565)
      871  WRITE(6,70566)
      872  WRITE(6,70567)
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      874  WRITE(6,70569)
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      905  WRITE(6,70600)
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      907  WRITE(6,70602)
      908  WRITE(6,70603)
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      910  WRITE(6,70605)
      911  WRITE(6,70606)
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      913  WRITE(6,70608)
      914  WRITE(6,70609)
      915  WRITE(6,70610)
      916  WRITE(6,70611)
      917  WRITE(6,70612)
      918  WRITE(6,70613)
      919  WRITE(6,70614)
      920  WRITE(6,70615)
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      940  WRITE(6,70635)
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      945  WRITE(6,70640)
      946  WRITE(6,70641)
      947  WRITE(6,70642)
      948  WRITE(6,70643)
      949  WRITE(6,70644)
      950  WRITE(6,70645)
      951  WRITE(6,70646)
      952  WRITE(6,70647)
      953  WRITE(6,70648)
      954  WRITE(6,70649)
      955  WRITE(6,70650)
      956  WRITE(6,70651)
      957  WRITE(6,70652)
      958  WRITE(6,70653)
      959  WRITE(6,70654)
      960  WRITE(6,7
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60008 FORMAT(1X, [IMPEDANCE DATA])
60009 FORMAT(8X,[DATA POINT],1X,[1/SQRT(OMEGA)],7X,[REAL Z],13X,[IMAGINA G]
60010 *RYZC8X[FORMAT(FREQY(HZ),15,4,14.6),
7000 FORMATT(1X)]
ENC

465

PROGRAM LENGTH INCLUDING I/O BUFFERS
000745

FUNCTION ASSIGNMENTS

STATEMENT	ASSIGNMENTS	361	320	-	000231	360	-	000267
300	-	000084	000435	-	000464	20004	-	000506
4001	-	0000357	4303	-	000513	60009	-	000517
20002	-	0000511	20003	-	000536	6004	-	000557
60002	-	0000524	6003	-	000567	6008	-	000577
60006	-	0000561	6007	-	000615	-	-	-
6010	-	0000611	7000	-	-	-	-	-
BLOCK NAMES AND LENGTHS			A	-	001446	2	-	000010
SAEP	-	000745	-	012742	A	-	-	-
VARIABLE ASSIGNMENTS								
AMPI	-	0000670	AMPV	-	000667	A1	-	00000502 A2
C1	-	000002502	C2	-	0000512	F	-	0012431501 FILTC
FILTV	-	00000672	T1	-	0000673	T1	-	000003502
J	-	00000674	MPROB	-	0000663	N	-	0000677001 INDATI
NDATV	-	00000664	NN	-	0000675	NPROB	-	0000000501 OBS
P	-	00000667	PEFS	-	000006703	RZ	-	0000000503 SWITCH
S1	-	0000031502	S2	-	000004502	TSAEP	-	000012741501 TS1
TSV	-	0000031502	VFFF	-	00000653	VY	-	0000666502 VHINC1
W	-	00000676	WBPK	-	00000657	WFIN	-	0000661501 XFF
W1NC2	-	00000620502	WINIT	-	00000655	XH	-	00006251501 YHD
X1	-	00000620502	XINW	-	00000645	XS	-	00006251501 ZH
ZH	-	0000311501	-	-	-	-	-	-
STAFF OF CONSTANTS								
000470								
START OF TEMPORARIES								
000617								

START OF INDIRECTS
000635

UNUSED COMPILER SPACE
0007400

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```

SUBROUTINE GAUHHH
EXTERNAL MODEL
COMMON/X(200), OBS(+00), YD(000), XS(4000), F(200), X(200), RZ
COMMON/A1,S1,A2,S2,V(200),EPS(7)
COMMON/Z/NP,D08,P(7),BNDLWR(7),BNDUPR(7),BNDLWR(7)
DIMENSION P(7),BNDUPR(7),BNDLWR(7)

TS=0
CONTINUE
100 NP=7
P(1)=A1
P(2)=S1
P(3)=A2
P(4)=S2
P(5)=S2
P(6)=C2
P(7)=C2
TF(T$N.E.0) GO TO 110
DO 110 I=1,NP
BNDLWR(I)=P(I)**1000.
BNDUPR(I)=P(I)**001
115 CONTINUE
EPS2=EPS-6.
EPS2=EPS3=0.
MAXIT=100
GAMMA=.01
FYI=10
CALL GAUSAUS(NPROB,MODEL,N,OBS,NP,BNDLWR,BNDUPR,EPS1,EPS2,
     CAXIT,GAMMA,FNU,XS)
CONTINUE
110 CALL MODEL(NPROB,P,YMD,N,NP)
U=0.
V=0.
WR1=TE(6,6000)
DO 120 I=1,N
ERRR=YHDI(I)-DRS(I)
FERR2=FRR**2
U=U+ERR
S=S+ERR2
J=(I+1)/2
WRITE(6,6001) I,X(J),OSS(I),YMD(I),ERR,ERR2
120 CONTINUE
U=U/N
S=SRT(S/N)
WRITE(6,6001) H,U,S
WRITE(6,6001) HETURN(I,P(I),I=1,NP)
ENTRY GAULLL
125 TO 126
126 FORMAT(1X,I15,4,2(1PE20,.3))
127 FORMAT(1X,I15,2(1P-2U,.3))
128 FORMAT(1X,I15,2(1F-2U,.3))
129 FORMAT(1X,I15,2(1F-2U,.3))

```

נְנָמָרֶת הַלְּבָנָה מִבְּרֹאָה נְנָמָרֶת
נְנָמָרֶת הַלְּבָנָה מִבְּרֹאָה נְנָמָרֶת

26

17 SUBROUTINE MODEL(NPROB,0,6,NG,NQ),YMD(800),XSC(4000),F(200),RZ,TSI(200),
COMMON/A1,S1,C1,A2,S2,VV,W1,W2,ZC1,ZC2,Z1,Z2,G
DCMPLX,X,UI,WT

```

COMPLEX X,UI,W1,W2,ZC1,ZC2,Z1,Z2,G
DATA A1,B1,C1,D1,E1,F1,G1,H1,I1,J1,K1,L1,M1,N1,O1,P1,Q1,R1,S1,T1,U1,V1,W1,X1,Y1,Z1
A1=0.01
B1=0.02
C1=0.03
D1=0.04
E1=0.05
F1=0.06
G1=0.07
H1=0.08
I1=0.09
J1=0.10
K1=0.11
L1=0.12
M1=0.13
N1=0.14
O1=0.15
P1=0.16
Q1=0.17
R1=0.18
S1=0.19
T1=0.20
U1=0.21
V1=0.22
W1=0.23
X1=0.24
Y1=0.25
Z1=0.26
A2=0.01
B2=0.02
C2=0.03
D2=0.04
E2=0.05
F2=0.06
G2=0.07
H2=0.08
I2=0.09
J2=0.10
K2=0.11
L2=0.12
M2=0.13
N2=0.14
O2=0.15
P2=0.16
Q2=0.17
R2=0.18
S2=0.19
T2=0.20
U2=0.21
V2=0.22
W2=0.23
X2=0.24
Y2=0.25
Z2=0.26
C1=0.01
C2=0.02
C3=0.03
C4=0.04
C5=0.05
C6=0.06
C7=0.07
C8=0.08
C9=0.09
C10=0.01
C11=0.02
C12=0.03
C13=0.04
C14=0.05
C15=0.06
C16=0.07
C17=0.08
C18=0.09
C19=0.01
C20=0.02
C21=0.03
C22=0.04
C23=0.05
C24=0.06
C25=0.07
C26=0.08
C27=0.09
C28=0.01
C29=0.02
C30=0.03
C31=0.04
C32=0.05
C33=0.06
C34=0.07
C35=0.08
C36=0.09
C37=0.01
C38=0.02
C39=0.03
C40=0.04
C41=0.05
C42=0.06
C43=0.07
C44=0.08
C45=0.09
C46=0.01
C47=0.02
C48=0.03
C49=0.04
C50=0.05
C51=0.06
C52=0.07
C53=0.08
C54=0.09
C55=0.01
C56=0.02
C57=0.03
C58=0.04
C59=0.05
C60=0.06
C61=0.07
C62=0.08
C63=0.09
C64=0.01
C65=0.02
C66=0.03
C67=0.04
C68=0.05
C69=0.06
C70=0.07
C71=0.08
C72=0.09
C73=0.01
C74=0.02
C75=0.03
C76=0.04
C77=0.05
C78=0.06
C79=0.07
C80=0.08
C81=0.09
C82=0.01
C83=0.02
C84=0.03
C85=0.04
C86=0.05
C87=0.06
C88=0.07
C89=0.08
C90=0.09
C91=0.01
C92=0.02
C93=0.03
C94=0.04
C95=0.05
C96=0.06
C97=0.07
C98=0.08
C99=0.09
C100=0.01
C101=0.02
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SUBROUTINE PARTIAL(NGD0,NG,NG0)
COMMON N,X(2C),OBS(40),YMD(800),XS(4000),F(200),RZ
DIMENSION I(1),NGD0(NG,NG)
D0120 I=1 NO
P=PS12=.5/PEPS(I)
QSAVE=Q(I)
Q(I)=QSAVE+PEPS(I)
CALL MODEL(NPROB,I,NGD0(I,I),NG,NG)
Q(I)=QSAVE-PEPS(I)
CALL MODEL(NPROB,0,YMD(1),NG,NG)
Q(I)=QSAVE
D0120 J=1 NG
D0120 J=(D6D0(J,I)-YMD(J,I))*PEPS12
CONTINUE
120 RETURN
FNC
```

SUBPROGRAM LENGTHS
000105

FUNCTION ASSIGNMENTS

STATEMENT ASSIGNMENTS

BLOCK NAMES AND LENGTHS

VARIABLE	ASSIGNMENTS	-	012742	2	-	000010
O3S	012431S01 I	=	000101	JPEPS12	-	000104
X	000311S01 PEPS	=	002571S12	YMD	-	000102
	0000311S01 XS	-	002571S12	QSAVE	-	000103

START OF CONSTANTS

SIAPT OF TEMPORARIES

START OF INDIRECTS

UNUSED COMPILER SPACE
011200

SUBPROGRAM LENGTH	000143
FUNCTION ASSIGNMENTS	
STATEMENT ASSIGNMENTS	-
1 000147	2 000106
BLOCK NAMES AND LENGTHS	
CTANH	- 000143
VARIABLE ASSIGNMENTS	
CTANH	- 000137
UI	- 000141
START OF CONSTANTS	
000115	
START OF TEMPORARIES	
000123	
START OF INDIRECTS	
000137	
UNUSED COMPILER SPACE	
011200	

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SUBROUTINE IFXFRM(INDAT,I,VT,W,VW)
C THIS SUBROUTINE COMPUTES THE LAPLACE TRANSFORM AT ANGULAR FREQUENCY
C OF THE SET OF ORDERED PAIRS T AND VT CORRESPONDING TO TIME AND
C FUNCTION VALUE AT THAT TIME EACH ZERO AT INFINITE TIME AND CANNOT CROSS ZERO.
C DIMENSION T(20),VT(20)
C COMPLEX VW,CA,CI,CIA,CA1,CIP1
C VW=CMPLEX(C,.C.)
C DO 100 I=1,IN
C 100 I=I+1
C IP=I+1
C IF(VT(IP).EQ.0.C) VT(I)=0.00001
C IF(VT(IP).LT.0.C) VT(I)=0.00001
C IF(VT(IP).GT.0.C) GO TO 150
C IA= ALOG(VT(IP)/VT(I)) /((I-I)-T(IP))
C CA= CMPLEX(A,.W)
C CIP=CMPLEX(0,.W*T(I))
C VW=VW+(VT(I)*CEXP(CI)-VT(I)*CEXP(CIP))/CA
C DT=(T(IP)-T(I))/T(I)
C B=(VT(IP)-DT*VT(I))/(1-DT)
C A=(VT(I)-B)/T(I)
C CA1=CMPLEX(C,.W)
C CIP1=CEXP(-CA1*T(IP))/CA1
C VW=VW+A*(CI1*(T(I)+1./CA1)-CIP1*(T(IP)+1./CA1))+B*(CI1-CIP1)
C CONTINUE
C VW=VW+VT(IP)*CEXP(CIP)/CA
C RETURN
ENC

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SUBPROGRAM LENGTH	000420
FUNCTION ASSIGNMENTS	
STATEMENT ASSIGNMENTS	
100 - 000255	101 - 000312
BLOCK NAMES AND LENGTHS	
BLPKFRM - 000420	
VARIABLE ASSIGNMENTS	
A - 000415	B - 000417
C1 - 000406	CIP - 000402
D1 - 000416	I - 000413
START OF CONSTANTS	
000315	

